ROLE OF THE STREAKY STRUCTURES IN A TRANSITION MECHANISM OF THE BOUNDARY LAYERS AND JETS

M.V. Litvinenko[1], **V.G. Chernorai**[1], **V.V. Kozlov**[2], **G.R. Grek**[2], **and L.L. Lofdal**[1]

[1] Chalmers University of Technology, S-412 96 Göteborg, Sweden
[2] Institute of Theoretical and Applied Mechanics SB RAS, 630090 Novosibirsk, Russia

Introduction

At present heightened interest of the researches is aimed at study of the stationary and non-stationary streamwise localized disturbances caused by the importance of their role during laminar-turbulent transition in various shear flows. It is known, that the distortion of mean velocity profiles in shear flow, i.e. presence on them of inflection points, result in such flow to instability concerning to secondary high-frequency disturbances. The concept of secondary high-frequency instability is confirmed by numerous experimental studies, in particular for near-wall shear flows, in which the flow is modulated in a spanwise direction by streamwise stationary vortices such as Goertler vortices [1] and cross-flow vortices on swept wings [2]. The modulation of mean flow by such vortices creates local velocity gradients both on a normal to a surface ($\partial U/\partial y$), and in a spanwise direction ($\partial U/\partial z$). Just in regions with inflection points on velocity profiles the secondary disturbances begin to grow. The streamwise disturbances, localized in spanwise direction can be stationary and non-stationary. Typical example of such disturbances are so-called streaky structures, which observed in a boundary layer at high free stream turbulence or in a viscous sublayer of a turbulent boundary layer. The streaky structures for the first time are modelled in experiments [3]. The measurements have shown, that on these structures can arise (for the various reasons, including their interaction with high-frequency waves) the secondary disturbances, which development downstream results in the turbulent spots origination. As well as in case of stationary streamwise structures, the non-stationary streaky structures travelling downstream locally distort mean flow. In this case, the local instability regions can to provoke the secondary disturbances growth.

Instability of jet flows usually connects to instability of vortical rings, so-called Kelvin – Helmholtz vortices. Dynamics of development process and breakdown of the ring vortices was studied by many investigators, for example [4]. The numerous theoretical and experimental researches of a streamwise vortical structures role during turbulisation of free shear flows, for example of jets were conducted. The streamwise structures form in regions between the neighbouring vortical rings and essential influence on processes of the flow mixing and dynamics [5]. In comparison with the round jet the flat jet is investigated much better. The theory describing life cycle of the coherent structures in a shear layer was found. In this case the mixing process in a shear layer is determined in main of the Kelvin – Helmholtz vortices. Between these vortices, just as in a round jet, the streamwise vortices arise and develop. However during development of a flat jet their role is negligible [6], in comparison with a round jet.

Thus, the role of streamwise structures during transition to turbulence both in near-wall and in free shear flows in many cases is determinative. The purpose of present study is the analysis of results of experimental researches of mechanisms of origin, development and transition to turbulent state of the various shear flows with the streamwise structures which have been carried out of late.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
23 Aug 2002	N/A	-

Title and Subtitle Role of the Streaky Structures in a Transition Mechanism of the Boundary Layers and Jets	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Institute of Theoretical and Applied Mechanics Institutskaya 4/1 Novosibirsk 530090 Russia	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) EOARD PSC 802 Box 14 FPO 09499-0014	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes See also ADM001433, Conference held International Conference on Methods of Aerophysical Research (11th) Held in Novosibirsk, Russia on 1-7 Jul 2002	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 6	

1. Boundary layer

Stationary streamwise vortices. As is known, the instability of boundary-layer flows on concave surfaces, swept wings and in some other cases results in origin of the streamwise stationary vortices. The reason of their occurrence in the first case are the centrifugal forces and in second case are crossflow caused by the secondary flow over a wing which leading edge is inclined under an angle to the basic flow. Origin of such vortices involve a primary instability of the flow. The transition to turbulence in considered cases is connected to development of the secondary high-frequency disturbances in regions with unstable velocity profiles both in spanwise and in normal to a wall directions. Such instability of profiles is created by the flow modulation by streamwise stationary vortices. Studies in [7] of "natural" transition has shown, that the high-frequency, secondary disturbances such as travelling waves were observed on the stationary vortices. Origin of the secondary vortices, which are superimposed on the primary stationary vortices and are spread along them is preceded the transition to turbulence. In the majority of the studies the qualitative characteristics (visualization pictures) perturbed flow in three-dimensional boundary layers are shown mainly, however the quantitative information concerning the disturbances origin and development in conditions of a spanwise modulation of the flow is necessary for the analysis of the transition process in them. Such information can be obtained in controlled experiments, that allows in more details to study the mechanism of either "natural" (uncontrollable) phenomenon, as a rule, it is proceeded simultaneously with processes of other physical nature. Method modelling of a three-dimensional stationary distortion of the flat plate laminar boundary layer was designed and applied in work [8]. Should be taken on the important result obtained in this work for the travelling waves: the increasing factors of the disturbances amplitudes in a modulated boundary layer are less, than in case of a flat plate unperturbed boundary layer. Hence, a stationary disturbed boundary layer is more steady concerning of Tollmien – Schlichting waves effect than undisturbed. It should be noted, that at the presence of the stationary vortices, the dependence of the phase velocity of the waves concerning of their propagation angle, i.e. dispersion, has not observed. In experiments [9] the vortices in a boundary layer were generated by roughness elements located periodically on a flat plate along z axis (Fig. 1,a).

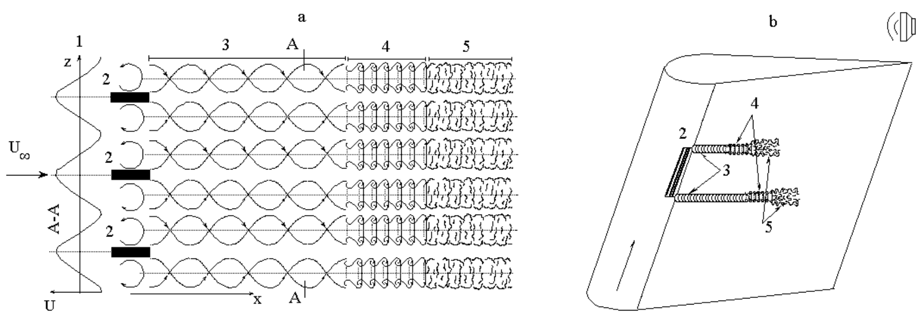

Fig. 1. Schemes of the transition in the flat plate (a) [9] and swept wing (b) [12] boundary layers modulated by streamwise structures. 1 – spanwise velocity distribution; 2 – roughness elements; 3 – streamwise structures; 4 – secondary disturbances; 5 – turbulence. Secondary disturbances were excited by vibrating ribbon (a), acoustic and blowig-suction (b).

In such case the experiment is modelled a transition in flow above a concave surface. The transition inside stationary vortices is provoked by amplification of the small amplitude waves created by a vibrating ribbon. The detected travelling disturbances have the inviscid nature and are connected to instability of a sinusoidal type [3]. As the flow simple enough, it has allowed in details to study the characteristics of waves and transition to turbulence. The similar mechanism of breakdown of a streamwise stationary vortex of large intensity generated in a boundary layer of a swept wing with the help of roughness elements is studied in a work [10] (Fig. 1, b). In a swept wing boundary layer in "natural" conditions [11] the packet of waves travelling on stationary vortices is found. Downstream development of this packet result in turbulence. It is shown, that the acoustic field with frequency relevant to a natural wave packet excites the travelling disturbances, which grow downstream and the laminar-turbulent transition in this case is moved upstream. The higher harmonics generation process at nonlinear stage of the travelling waves development is fixed. On the basis of these results, the basis pair of the "natural" small intensity stationary vortices on a swept wing are modelled and the development characteristics both vortices and high-frequency disturbances travelling on them were studied [12]. It is shown, that the mean velocity distributions and streamwise velocity fluctuation component in spanwise direction are various for each structure. The range of linear development of secondary disturbances is determined and their characteristics are investigated. Decrease of the distance between vortices due to the modification of the roughness element length in spanwise direction result in vortices interaction. It is experimentally found, that the disturbances development on a single vortex is similar to instability growing on the vortices group with large periodicity in spanwise direction. Vortices interaction becomes essential with reduction of distance between them: than it is less growth rates of travelling waves become less. It is explained by distributions of the streamwise and normal velocity components in vortices. The amplitude of waves in all considered cases was greatest near to maxima of shear (gradients) of velocity in a spanwise direction. It testifies that the behaviour of disturbances can be determined by mechanisms of an inflexion (inviscid) instability.

Nonstationary streamwise vortices. In a flat plate boundary layer the localized three-dimensional disturbances generated by roughness elements [13] or various transient disturbances [14] result in generation of streamwise vortical structures, which locally change a spanwise flow pattern and create the conditions for secondary instability. The Λ-structures of nonlinear stage of the classical transition concern to the nonstationary localized disturbances. Modelling of a single Λ-structure in a flat plate boundary layer [15] have shown, that depending on the disturbance amplitude can exist both the decreasing and increasing Λ-structures. Moreover, when interacting the decreasing Λ-structure and the high-frequency wave with intensity less than 1 % the high-frequency wave packet is generated on the Λ-structure "legs" which develops downstream and this process result in transformation of the Λ-structure into the turbulent spot. At a high free stream turbulence the continuous penetration of the disturbances from free stream into a boundary layer results in excitation of the streamwise structures (streaky structures) locally modulating a boundary layer [3]. In these flows, as well as in case of transition of a three-dimensional boundary layer modulated by stationary vortices, the transition to turbulence is connected to stability of streamwise vortical structures. The streaky structures are observed also in a viscous sublayer of a turbulent boundary layer. Origin of these structures is explained by so-called "lift-up effect" described within the framework of the algebraic instability theory [16]. In contrast with the stationary vortices, the streaky structures have a very weak vorticity and represent the narrow layers of a liquid with defect/excess velocity alternating in a spanwise direction. Nevertheless instability of the flows modulated by streaky structures is

connected to the spanwise velocity gradients, as well as in case of their modulation by stationary vortices. This statement is confirmed by the experiments in controlled conditions on the basis of which the transition scenario at high free stream turbulence is suggested [3]. The development of the secondary high-frequency disturbances in the field of unstable mean velocity profiles on spanwise direction in flow with streaky structures results in origin of high-frequency packets which transforms into the turbulent spots downstream. The present process can occur as at interaction of a to a high-frequency wave and as a result of the increase, under certain conditions, of high-frequency component contained inside of the streaky structure [3]. Thus, the analysis of results of the experimental studies which have been carried out recently shows, that the transition to turbulence in boundary layers with the streamwise stationary and nonstationary localized disturbances is connected to development on them of secondary high-frequency disturbances.

2. Jet flows

Round jet. The studies of a round jet development dynamics have shown, that the streamwise structures localized in region of a jet shear layer originate directly on a nozzle outlet due to the lift-up effect. Development dynamics of these structures is similar to development dynamics of the streaky structures in a boundary layer [17]. In particular, in controlled conditions is shown, that on them the secondary high-frequency disturbances can develop that results in acceleration of a jet turbulisation. The natural streaky structures observed near to the nozzle outlet at Re≈10 600 were reproduced by artificially with help of the roughness elements pasted on an inside nozzle surface which sizes correlated with a scale of the "natural" streamwise structures. The high-frequency disturbance was introduced through a small hole on the nozzle surface located near to a roughness element with help of the air blowing-suction. The interaction of a streaky structure with a high-frequency disturbance results in growth of this streaky structure intensity (Fig. 2). Disturbance intensity is increased downstream and the next streaky structures are involved in this process. The jet turbulisation is accelerated. Thus, is shown, that the instability of the round jet can be connected to origin of the streamwise localized disturbances (streaky structures) directly on the nozzle outlet.

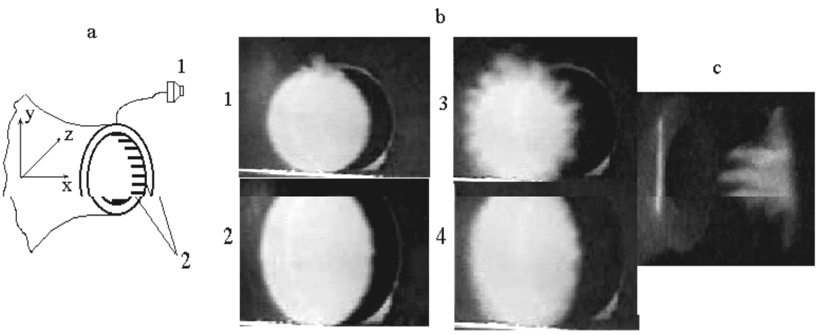

Fig. 2. Streamwise structures in the round jet and their secondary instability [17]. Experimental set-up (a): 1 – source of secondary disturbances, 2 – roughness elements; Visualization pictures of the jet in y–z plane (b): 1, 3 – with secondary disturbances, 2, 4 – without secondary disturbances; x = 8 mm (1,3), x = 16 mm (2,4); Visualization pictures of the jet in x-y plane (c), x = 28 mm; U_∞=4 m/s.

The instability of the streaky structures to high-frequency secondary disturbances promotes acceleration of the jet turbulisation. The present result agrees with results of the instability study of the boundary layer modulated by streaky structures.

Flat jet. Studies of the plain jet in a nearfield [18] have shown, as in this case there can be streaky structures (Fig. 3).

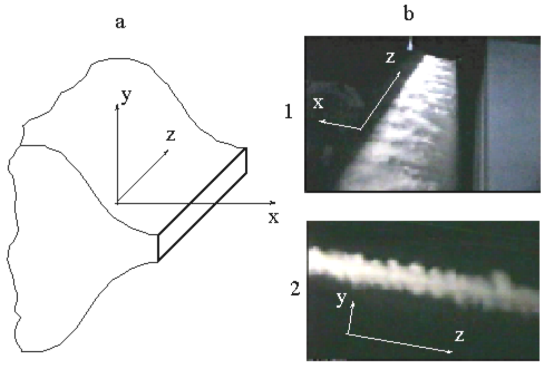

Fig. 3. Streamwise structures in the plane jet [18]. Experimental set-up (a); Visualization pictures of the plane jet (b): 1 – in x-z plane, 2 – in y-z plane; U_∞=7.3 m/s, x=8 mm.

In contrast to of the round jet the secondary disturbance develops only on the streaky structure where it was artificial is exited not involving in this process the next structures.

Conclusions

The analysis of the laminar-turbulent transition has shown, that in various shear flows, such as boundary layers and jets, are observed the streamwise localized structures. In this case, the breakdown mechanism of a laminar flow is connected to the secondary high-frequency instability of the flows modulated by such streaky structures. This process is qualitatively identical both for the stationary and nonstationary streamwise localized structures, such as Goertler vortices, crossflow vortices on a swept wing, streaky structures at a high free stream turbulence and also, probably, for the coherent structures of a viscous sublayer of a turbulent boundary layer. For more clear understanding of the mechanism of laminar-turbulent transition and capabilities of control of this process are necessary further studies of the development characteristics of these structures and their secondary high-frequency instability.

Acknowledgements. The work was supported by the Russian Basic for Sciences Foundation (grants Nos. 00-15-96164 and 02-01-00006) and INTAS (grants No. 00-00232 and No. YSF00-61)

REFERENCES

1. **Kohama Y., Fukunishi Y., Wang T.-J.** The response of artificial longitudinal vortex pair embedded in the boundary layer to acoustic excitation // JSME Intern. J., Ser. B. 1993. Vol. 36. P. 74-79.
2. **Saric W.S., Yeates L.G.** Generation of crossflow vortices in a three-dimensional flat plate flow // Laminar-turbulent transition. Berlin: Springer-Verlag, 1985. P. 429-437.
3. **Boiko A.V., Grek G.R., Dovgal A.V., Kozlov V.V.** Origin of turbulence in near-wall flows. Novosibirsk: Nauka, 1999 (in Russian).
4. **Kopiev V.F., Chernishev S.A.** Oscillations of a vortical ring, origin in it(him) of turbulence and oscillation of a sound // Successes of Phys. Sci. 2000. Vol. 170, No. 7. P. 713-742 (in Russian).
5. **Liepmann D., Gharib, M.** The role of streamwise vorticity in the near-field entrainment of round jets // J. Fluid Mech. 1992. Vol. 245. P. 643-668.

6. **Lin S. J., Corcos, G. M.** The mixing layer: deterministic models of a turbulent flow. Pt 3. The effect of plain strain on the dynamics of streamwise vortices // J. Fluid Mech. 1984. Vol. 141. P. 139-178.
7. **Kohama Y.** Some expectation on the mechanism of crossflow instability in a swept wing flow // Acta Mech.1987. Vol. 66. P. 21-38.
8. **Kachanov Yu. S., Tararikin O.I.** About. And. Experimental research of a relaxing boundary layer // Izv. AN SSSR. Ser. Techn. Nauk. 1987. Vyp. 5. P. 9-19 (in Russian).
9. **Bakchinov A.A., Grek H.R., Klingmann B.G.B., Kozlov V.V.** Transition experiments in a boundary layer with embedded streamwise vortices // Phys. Fluids. 1995. Vol. 7. P. 820-832.
10. **Boiko A.V., Kozlov V.V., Syzrancev V.V., Sherbakov V.A**. Experimental research of process of transition to turbulence on a single stationary disturbance in a boundary layer of a swept wing // PMTF. 1995. Vol. 36, No. 1. P. 72-84 (in Russian).
11. **Kozlov V.V., Levchenko V.Ya., Sova V.A., Sherbakov V.A.** Influence of an acoustic field on structure of flow and laminar - turbulent transition on a swept wing. // Proc. of Sympos. "Modern Problems of an Aerohydromechanics", Moscow, April 12-15 1999. M., 1999. Vol. 2. P. 145-155 (in Russian**).**
12. **Kozlov V.V., Sova V.A., Sherbakov V.A.** Experimental research of development of secondary disturbances on a swept wing // Mechanics of a Liquid and Gas. 2001. No. 5. P. 92-98 (in Russian).
13. **Mochizuki M.** Smoke observation on boundary layer transition caused by a spherical roughness element // J. Phys. Soc. Japan. 1961. Vol. 16. P. 995-1012.
14. **Grek G.R., Kozlov V.V., Ramasanov M.P.** Three types of disturbances from the point source in the boundary layer // Laminar-turbulent transition. Berlin: Springer-Verlag, 1985. P. 267-272.
15. **Grek G.R., Kozlov V.V., Katasonov M.M., Chernorai V.G.** Experimental study of a Λ-structure and its transformation into the turbulent spot // Current Sci. 2000. Vol. 79. No. 6. P. 781-789.
16. **Landahl M.L.** A note on an algebraic instability of inviscid parallel shear flows // J. Fluid Mech. 1980. Vol. 98. P. 243-251.
17. **Kozlov V.V., Bakchinov A.A., Lofdal L.L., Chernorai V.G**. Streamwise structures in boundary layers and jets // 8th Intern. Conf. "Stability of Flows of Homogeneous and Heterogeneous Liquids": Abstr. Novosibirsk: ITAM SB RAS, 2001. P. 84 (in Russian).
18. **Chernoray V.G., Bakchinov A.A., Kozlov V.V., Lofdahl L.L.** The role of streamwise structures in the near-field entrainment of plane jet // Book of Abstr. of 426th Euromech, Ercoftac Colloquium on Swirling Flows, Bergen-Tromso [Norway], 16-20 Sept. 2001. Trondheim: Norwegian Technology Univer., 2001. P. 9-10.